

Overview of the Circulation; Biophysics of Pressure, Flow, and Resistance

The function of the circulation is to serve the needs of the body tissues—to transport nutrients to the body tissues, to transport waste products away, to transport hormones from one part of the body to another and, in general, to maintain an appropriate environment in all the tissue fluids of the body for survival and optimal function of the cells.

The rate of blood flow through many tissues is controlled mainly in response to their need for nutrients. In some organs, such as the kidneys, the circulation serves additional functions. Blood flow to the kidney, for example, is far in excess of its metabolic requirements and is related to its excretory function, which requires that a large volume of blood be filtered each minute.

The heart and blood vessels, in turn, are controlled to provide the necessary cardiac output and arterial pressure to cause the needed tissue blood flow. What are the mechanisms for controlling blood volume and blood flow, and how does this process relate to the other functions of the circulation? These are some of the topics and questions that we discuss in this section on the circulation.

PHYSICAL CHARACTERISTICS OF THE CIRCULATION

The circulation, shown in [Figure 14-1](#), is divided into the *systemic circulation* and the *pulmonary circulation*. Because the systemic circulation supplies blood flow to all the tissues of the body except the lungs, it is also called the *greater circulation* or *peripheral circulation*.

Functional Parts of the Circulation. Before discussing the details of circulatory function, it is important to understand the role of each part of the circulation.

The function of the *arteries* is to transport blood *under high pressure* to the tissues. For this reason, the arteries have strong vascular walls, and blood flows at a high velocity in the arteries.

The *arterioles* are the last small branches of the arterial system; they act as *control conduits* through which blood is released into the capillaries. Arterioles have strong

muscular walls that can close the arterioles completely or can, by relaxing, dilate the vessels severalfold, thus having the capability of vastly altering blood flow in each tissue in response to its needs.

The function of the *capillaries* is to exchange fluid, nutrients, electrolytes, hormones, and other substances between the blood and the interstitial fluid. To serve this role, the capillary walls are thin and have numerous minute *capillary pores* permeable to water and other small molecular substances.

The *venules* collect blood from the capillaries and gradually coalesce into progressively larger veins.

The *veins* function as conduits for transport of blood from the venules back to the heart; equally important, they serve as a major reservoir of extra blood. Because the pressure in the venous system is very low, the venous walls are thin. Even so, they are muscular enough to contract or expand and thereby serve as a controllable reservoir for the extra blood, either a small or a large amount, depending on the needs of the circulation.

Volumes of Blood in the Different Parts of the Circulation. [Figure 14-1](#) gives an overview of the circulation and lists the percentage of the total blood volume in major segments of the circulation. For instance, about 84 percent of the entire blood volume of the body is in the systemic circulation and 16 percent is in the heart and lungs. Of the 84 percent in the systemic circulation, approximately 64 percent is in the veins, 13 percent is in the arteries, and 7 percent is in the systemic arterioles and capillaries. The heart contains 7 percent of the blood, and the pulmonary vessels, 9 percent.

Most surprising is the low blood volume in the capillaries. It is here, however, that the most important function of the circulation occurs—diffusion of substances back and forth between the blood and the tissues. This function is discussed in detail in Chapter 16.

Cross-Sectional Areas and Velocities of Blood Flow. If all the *systemic vessels* of each type were put side by side, their approximate total cross-sectional areas for the average human being would be as follows:

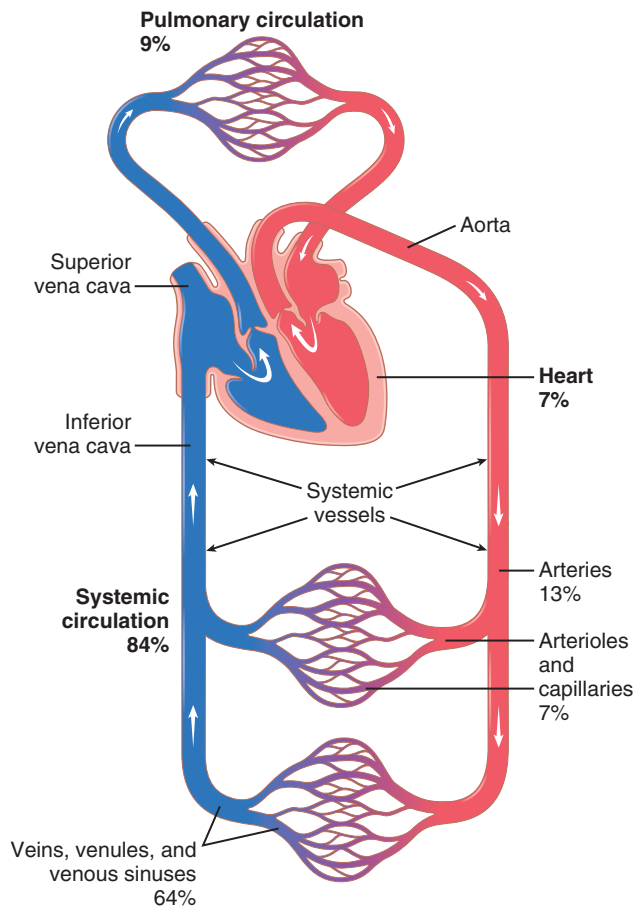


Figure 14-1. Distribution of blood (in percentage of total blood) in the different parts of the circulatory system.

| Vessel | Cross-Sectional Area (cm ²) |
|----------------|---|
| Aorta | 2.5 |
| Small arteries | 20 |
| Arterioles | 40 |
| Capillaries | 2500 |
| Venules | 250 |
| Small veins | 80 |
| Venae cavae | 8 |

Note particularly that the cross-sectional areas of the veins are much larger than those of the arteries, averaging about four times those of the corresponding arteries. This difference explains the large blood storage capacity of the venous system in comparison with the arterial system.

Because the same volume of blood flow (F) must pass through each segment of the circulation each minute, the velocity of blood flow (v) is inversely proportional to vascular cross-sectional area (A):

$$v = F/A$$

Thus, under resting conditions, the velocity averages about 33 cm/sec in the aorta but is only 1/1000 as rapid in the capillaries—about 0.3 mm/sec. However, because the capillaries have a typical length of only 0.3 to 1

millimeter, the blood remains in the capillaries for only 1 to 3 seconds, which is surprising because all diffusion of nutrient food substances and electrolytes that occurs through the capillary walls must be performed in this short time.

Pressures in the Various Portions of the Circulation. Because the heart pumps blood continually into the aorta, the mean pressure in the aorta is high, averaging about 100 mm Hg. Also, because heart pumping is pulsatile, the arterial pressure alternates between a *systolic pressure level* of 120 mm Hg and a *diastolic pressure level* of 80 mm Hg, as shown on the left side of **Figure 14-2**.

As the blood flows through the *systemic circulation*, its mean pressure falls progressively to about 0 mm Hg by the time it reaches the termination of the superior and inferior venae cavae where they empty into the right atrium of the heart.

The pressure in the systemic capillaries varies from as high as 35 mm Hg near the arteriolar ends to as low as 10 mm Hg near the venous ends, but their average “functional” pressure in most vascular beds is about 17 mm Hg, a pressure low enough that little of the plasma leaks through the minute *pores* of the capillary walls, even though nutrients can *diffuse* easily through these same pores to the outlying tissue cells.

Note at the far right side of **Figure 14-2** the respective pressures in the different parts of the *pulmonary circulation*. In the pulmonary arteries, the pressure is pulsatile, just as in the aorta, but the pressure is far less: *pulmonary artery systolic pressure* averages about 25 mm Hg and *diastolic pressure* averages about 8 mm Hg, with a mean pulmonary arterial pressure of only 16 mm Hg. The mean pulmonary capillary pressure averages only 7 mm Hg. Yet, the total blood flow through the lungs each minute is the same as through the systemic circulation. The low pressures of the pulmonary system are in accord with the needs of the lungs because all that is required is to expose the blood in the pulmonary capillaries to oxygen and other gases in the pulmonary alveoli.

BASIC PRINCIPLES OF CIRCULATORY FUNCTION

Although the details of circulatory function are complex, three basic principles underlie all functions of the system.

1. *Blood flow to most tissues is controlled according to the tissue need.* When tissues are active, they need a greatly increased supply of nutrients and therefore much more blood flow than when at rest—occasionally as much as 20 to 30 times the resting level. Yet, the heart normally cannot increase its cardiac output more than four to seven times greater than resting levels. Therefore, it is not possible simply to increase blood flow everywhere in the body when a particular tissue demands increased flow. Instead, the microvessels of each

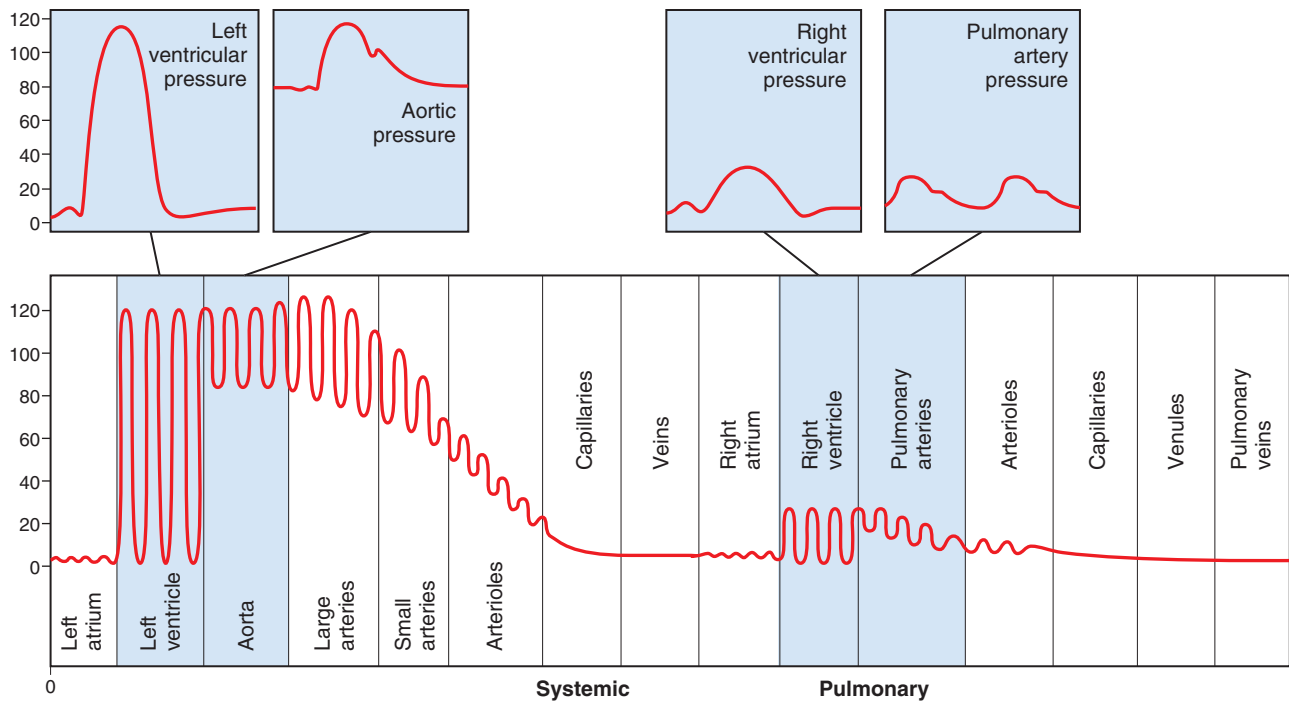


Figure 14-2. Normal blood pressures in the different portions of the circulatory system when a person is lying in the horizontal position.

tissue continuously monitor tissue needs, such as the availability of oxygen and other nutrients and the accumulation of carbon dioxide and other tissue waste products, and these microvessels in turn act directly on the local blood vessels, dilating or constricting them, to control local blood flow precisely to that level required for the tissue activity. Also, nervous control of the circulation from the central nervous system and hormones provide additional help in controlling tissue blood flow.

2. *Cardiac output is the sum of all the local tissue flows.* When blood flows through a tissue, it immediately returns by way of the veins to the heart. The heart responds automatically to this increased inflow of blood by pumping it immediately back into the arteries. Thus, the heart acts as an automaton, responding to the demands of the tissues. The heart, however, often needs help in the form of special nerve signals to make it pump the required amounts of blood flow.
3. *Arterial pressure regulation is generally independent of either local blood flow control or cardiac output control.* The circulatory system is provided with an extensive system for controlling the arterial blood pressure. For instance, if at any time the pressure falls significantly below the normal level of about 100 mm Hg, within seconds a barrage of nervous reflexes elicits a series of circulatory changes to raise the pressure back toward normal. The nervous signals especially (a) increase the force of heart pumping, (b) cause contraction of the large venous reservoirs to provide more blood to the heart, and (c) cause generalized constriction of the

arterioles in many tissues so that more blood accumulates in the large arteries to increase the arterial pressure. Then, over more prolonged periods—hours and days—the kidneys play an additional major role in pressure control both by secreting pressure-controlling hormones and by regulating the blood volume.

Thus, the needs of the individual tissues are served specifically by the circulation. In the remainder of this chapter, we begin to discuss the basic details of the management of tissue blood flow and control of cardiac output and arterial pressure.

INTERRELATIONSHIPS OF PRESSURE, FLOW, AND RESISTANCE

Blood flow through a blood vessel is determined by two factors: (1) *pressure difference* of the blood between the two ends of the vessel, also sometimes called “pressure gradient” along the vessel, which pushes the blood through the vessel, and (2) the impediment to blood flow through the vessel, which is called *vascular resistance*. **Figure 14-3** demonstrates these relationships, showing a blood vessel segment located anywhere in the circulatory system.

P_1 represents the pressure at the origin of the vessel; at the other end, the pressure is P_2 . Resistance occurs as a result of friction between the flowing blood and the intravascular endothelium all along the inside of the vessel. The flow through the vessel can be calculated by the following formula, which is called *Ohm’s law*:

$$F = \frac{\Delta P}{R}$$

in which F is blood flow, ΔP is the pressure difference ($P_1 - P_2$) between the two ends of the vessel, and R is the resistance. This formula states that the blood flow is directly proportional to the pressure difference but inversely proportional to the resistance.

Note that it is the *difference* in pressure between the two ends of the vessel, not the absolute pressure in the vessel, that determines rate of flow. For example, if the pressure at both ends of a vessel is 100 mm Hg and yet no difference exists between the two ends, there will be no flow despite the presence of 100 mm Hg pressure.

Ohm's law, illustrated in the preceding formula, expresses the most important of all the relations that the reader needs to understand to comprehend the hemodynamics of the circulation. Because of the extreme importance of this formula, the reader should also become familiar with its other algebraic forms:

$$\Delta P = F \times R$$

$$R = \frac{\Delta P}{F}$$

BLOOD FLOW

Blood flow means the quantity of blood that passes a given point in the circulation in a given period of time. Ordinarily, blood flow is expressed in *milliliters per*

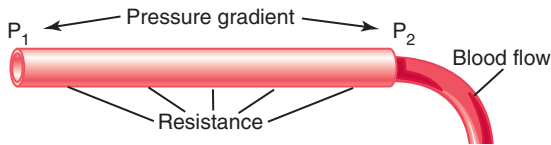


Figure 14-3. Interrelationships of pressure, resistance, and blood flow. P_1 , pressure at the origin of the vessel; P_2 , pressure at the other end of the vessel.

minute or *liters per minute*, but it can be expressed in milliliters per second or in any other units of flow and time.

The overall blood flow in the total circulation of an adult person at rest is about 5000 ml/min. This is called the *cardiac output* because it is the amount of blood pumped into the aorta by the heart each minute.

Methods for Measuring Blood Flow. Many mechanical and mechano-electrical devices can be inserted in series with a blood vessel or, in some instances, applied to the outside of the vessel to measure flow. These devices are called *flowmeters*.

Electromagnetic Flowmeter. A device for measuring blood flow experimentally without opening the vessel is the electromagnetic flowmeter, the principles of which are illustrated in **Figure 14-4**. **Figure 14-4A** shows the generation of electromotive force (electrical voltage) in a wire that is moved rapidly in a cross-wise direction through a magnetic field. This is the well-known principle for production of electricity by the electric generator. **Figure 14-4B** shows that the same principle applies for generation of electromotive force in blood that is moving through a magnetic field. In this case, a blood vessel is placed between the poles of a strong magnet, and electrodes are placed on the two sides of the vessel perpendicular to the magnetic lines of force. When blood flows through the vessel, an electrical voltage proportional to the rate of blood flow is generated between the two electrodes, and this voltage is recorded using an appropriate voltmeter or electronic recording apparatus. **Figure 14-4C** shows an actual "probe" that is placed on a large blood vessel to record its blood flow. The probe contains both the strong magnet and the electrodes.

A special advantage of the electromagnetic flowmeter is that it can record changes in flow in less than 1/100 of a second, allowing accurate recording of pulsatile changes in flow, as well as steady flow.

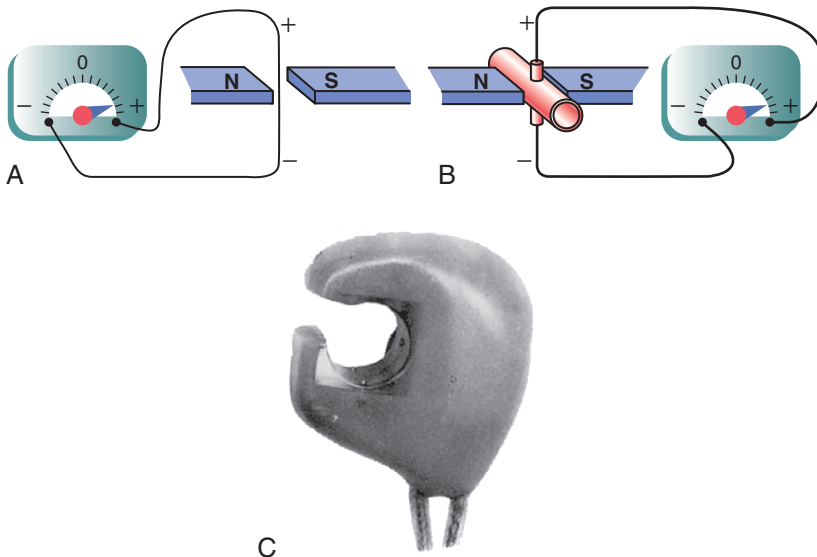


Figure 14-4. Flowmeter of the electromagnetic type, showing generation of an electrical voltage in a wire as it passes through an electromagnetic field (A); generation of an electrical voltage in electrodes on a blood vessel when the vessel is placed in a strong magnetic field and blood flows through the vessel (B); and a modern electromagnetic flowmeter probe for chronic implantation around blood vessels (C). N and S refer to the magnet's north and south poles.

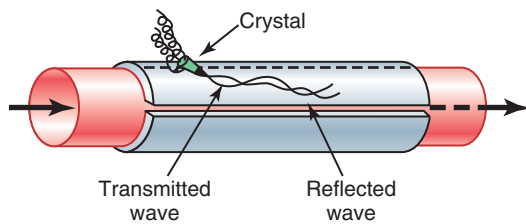


Figure 14-5. Ultrasonic Doppler flowmeter.

Ultrasonic Doppler Flowmeter. Another type of flowmeter that can be applied to the outside of the vessel and that has many of the same advantages as the electromagnetic flowmeter is the *ultrasonic Doppler flowmeter*, shown in Figure 14-5. A minute piezoelectric crystal is mounted at one end in the wall of the device. This crystal, when energized with an appropriate electronic apparatus, transmits ultrasound at a frequency of several hundred thousand cycles per second downstream along the flowing blood. A portion of the sound is reflected by the red blood cells in the flowing blood. The reflected ultrasound waves then travel backward from the blood cells toward the crystal. These reflected waves have a lower frequency than the transmitted wave because the red blood cells are moving away from the transmitter crystal. This effect is called the *Doppler effect*. (It is the same effect that one experiences when a train approaches and passes by while blowing its whistle. Once the whistle has passed by the person, the pitch of the sound from the whistle suddenly becomes much lower than when the train is approaching.)

For the flowmeter shown in Figure 14-5, the high-frequency ultrasound wave is intermittently cut off, and the reflected wave is received back onto the crystal and amplified greatly by the electronic apparatus. Another portion of the electronic apparatus determines the frequency difference between the transmitted wave and the reflected wave, thus determining the velocity of blood flow. As long as the diameter of a blood vessel does not change, changes in blood flow in the vessel are directly related to changes in flow velocity.

Like the electromagnetic flowmeter, the ultrasonic Doppler flowmeter is capable of recording rapid, pulsatile changes in flow, as well as steady flow.

Laminar Flow of Blood in Vessels. When blood flows at a steady rate through a long, smooth blood vessel, it flows in *streamlines*, with each layer of blood remaining the same distance from the vessel wall. Also, the central-most portion of the blood stays in the center of the vessel. This type of flow is called *laminar flow* or *streamline flow*, and it is the opposite of *turbulent flow*, which is blood flowing in all directions in the vessel and continually mixing within the vessel, as discussed subsequently.

Parabolic Velocity Profile During Laminar Flow. When laminar flow occurs, the velocity of flow in the center of the vessel is far greater than that toward the outer edges. This phenomenon is demonstrated in Figure 14-6. In

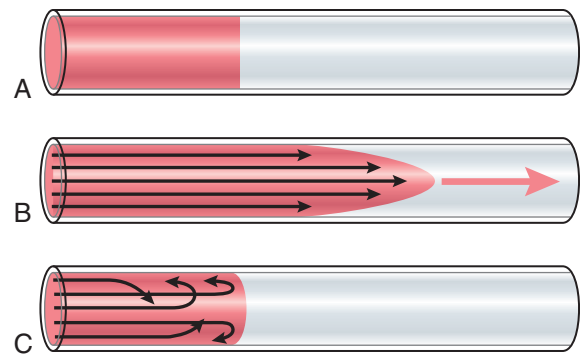


Figure 14-6. **A**, Two fluids (one dyed red, and the other clear) before flow begins. **B**, The same fluids 1 second after flow begins. **C**, Turbulent flow, with elements of the fluid moving in a disorderly pattern.

Figure 14-6A, a vessel contains two fluids, the one at the left colored by a dye and the one at the right a clear fluid, but there is no flow in the vessel. When the fluids are made to flow, a parabolic interface develops between them, as shown 1 second later in Figure 14-6B; the portion of fluid adjacent to the vessel wall has hardly moved, the portion slightly away from the wall has moved a small distance, and the portion in the center of the vessel has moved a long distance. This effect is called the “parabolic profile for velocity of blood flow.”

The cause of the parabolic profile is the following: The fluid molecules touching the wall move slowly because of adherence to the vessel wall. The next layer of molecules slips over these, the third layer over the second, the fourth layer over the third, and so forth. Therefore, the fluid in the middle of the vessel can move rapidly because many layers of slipping molecules exist between the middle of the vessel and the vessel wall; thus, each layer toward the center flows progressively more rapidly than the outer layers.

Turbulent Flow of Blood Under Some Conditions. When the rate of blood flow becomes too great, when it passes by an obstruction in a vessel, when it makes a sharp turn, or when it passes over a rough surface, the flow may then become *turbulent*, or disorderly, rather than streamlined (see Figure 14-6C). Turbulent flow means that the blood flows crosswise in the vessel and along the vessel, usually forming whorls in the blood, called *eddy currents*. These eddy currents are similar to the whirlpools that one frequently sees in a rapidly flowing river at a point of obstruction.

When eddy currents are present, the blood flows with much greater resistance than when the flow is streamlined, because eddies add tremendously to the overall friction of flow in the vessel.

The tendency for turbulent flow increases in direct proportion to the velocity of blood flow, the diameter of the blood vessel, and the density of the blood and is inversely proportional to the viscosity of the blood, in accordance with the following equation:

$$Re = \frac{v \cdot d \cdot \rho}{\eta}$$

where *Re* is *Reynolds' number* and is the measure of the tendency for turbulence to occur, *v* is the mean velocity of blood flow (in centimeters/second), *d* is the vessel diameter (in centimeters), *ρ* is density, and *η* is the viscosity (in poise). The viscosity of blood is normally about 1/30 poise, and the density is only slightly greater than 1. When Reynolds' number rises above 200 to 400, turbulent flow will occur at some branches of vessels but will die out along the smooth portions of the vessels. However, when Reynolds' number rises above approximately 2000, turbulence will usually occur even in a straight, smooth vessel.

Reynolds' number for flow in the vascular system normally rises to 200 to 400 even in large arteries; as a result there is almost always some turbulence of flow at the branches of these vessels. In the proximal portions of the aorta and pulmonary artery, Reynolds' number can rise to several thousand during the rapid phase of ejection by the ventricles, which causes considerable turbulence in the proximal aorta and pulmonary artery where many conditions are appropriate for turbulence: (1) high velocity of blood flow, (2) pulsatile nature of the flow, (3) sudden change in vessel diameter, and (4) large vessel diameter. However, in small vessels, Reynolds' number is almost never high enough to cause turbulence.

BLOOD PRESSURE

Standard Units of Pressure. Blood pressure almost always is measured in millimeters of mercury (mm Hg) because the mercury manometer has been used as the standard reference for measuring pressure since its invention in 1846 by Poiseuille. Actually, blood pressure means the *force exerted by the blood against any unit area of the vessel wall*. When one says that the pressure in a vessel is 50 mm Hg, this means that the force exerted is sufficient to push a column of mercury against gravity up to a level 50 millimeters high. If the pressure is 100 mm Hg, it will push the column of mercury up to 100 millimeters.

Occasionally, pressure is measured in *centimeters of water* (cm H₂O). A pressure of 10 cm H₂O means a pressure sufficient to raise a column of water against gravity to a height of 10 centimeters. *One millimeter of mercury pressure equals 1.36 centimeters of water pressure* because the specific gravity of mercury is 13.6 times that of water, and 1 centimeter is 10 times as great as 1 millimeter.

High-Fidelity Methods for Measuring Blood Pressure.

The mercury in a manometer has so much inertia that it cannot rise and fall rapidly. For this reason, the mercury manometer, although excellent for recording steady pressures, cannot respond to pressure changes that occur more rapidly than about one cycle every 2 to 3 seconds.

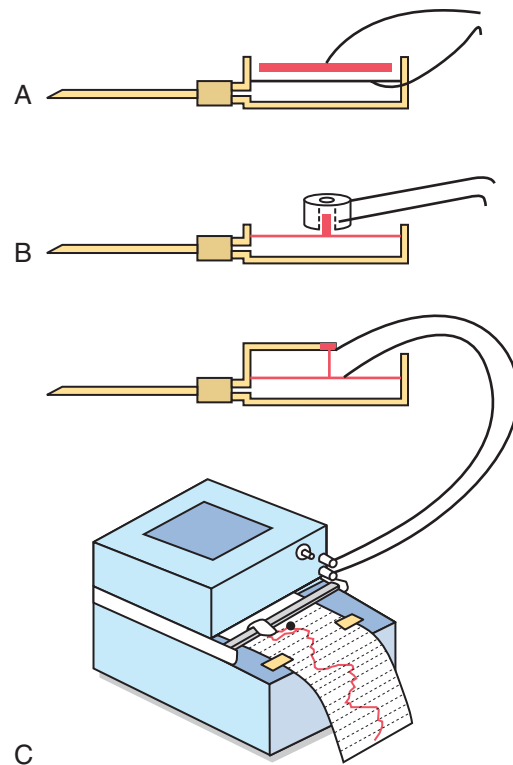


Figure 14-7. Principles of three types of electronic transducers for recording rapidly changing blood pressures (explained in the text).

Whenever it is desired to record rapidly changing pressures, some other type of pressure recorder is necessary.

Figure 14-7 demonstrates the basic principles of three electronic pressure *transducers* commonly used for converting blood pressure and/or rapid changes in pressure into electrical signals and then recording the electrical signals on a high-speed electrical recorder. Each of these transducers uses a very thin, highly stretched metal membrane that forms one wall of the fluid chamber. The fluid chamber in turn is connected through a needle or catheter inserted into the blood vessel in which the pressure is to be measured. When the pressure is high, the membrane bulges slightly, and when it is low, it returns toward its resting position.

In **Figure 14-7A**, a simple metal plate is placed a few hundredths of a centimeter above the membrane. When the membrane bulges, the membrane comes closer to the plate, which increases the *electrical capacitance* between these two, and this change in capacitance can be recorded using an appropriate electronic system.

In **Figure 14-7B**, a small iron slug rests on the membrane, and this slug can be displaced upward into a center space inside an electrical wire coil. Movement of the iron into the coil increases the *inductance* of the coil, and this, too, can be recorded electronically.

Finally, in **Figure 14-7C**, a very thin, stretched resistance wire is connected to the membrane. When this wire is stretched greatly, its resistance increases; when it is stretched less, its resistance decreases. These changes, too, can be recorded by an electronic system.

The electrical signals from the transducer are sent to an amplifier and then to an appropriate recording device. With some of these high-fidelity types of recording systems, pressure cycles up to 500 cycles per second have been recorded accurately. In common use are recorders capable of registering pressure changes that occur as rapidly as 20 to 100 cycles per second, in the manner shown on the recording paper in [Figure 14-7C](#).

RESISTANCE TO BLOOD FLOW

Units of Resistance. Resistance is the impediment to blood flow in a vessel, but it cannot be measured by any direct means. Instead, resistance must be calculated from measurements of blood flow and pressure difference between two points in the vessel. If the pressure difference between two points is 1 mm Hg and the flow is 1 ml/sec, the resistance is said to be 1 *peripheral resistance unit*, usually abbreviated *PRU*.

Expression of Resistance in CGS Units. Occasionally, a basic physical unit called the CGS (centimeters, grams, seconds) unit is used to express resistance. This unit is dyne sec/cm⁵. Resistance in these units can be calculated by the following formula:

$$R \left(\text{in } \frac{\text{dyne sec}}{\text{cm}^5} \right) = \frac{1333 \times \text{mm Hg}}{\text{ml/sec}}$$

Total Peripheral Vascular Resistance and Total Pulmonary Vascular Resistance. The rate of blood flow through the entire circulatory system is equal to the rate of blood pumping by the heart—that is, it is equal to the cardiac output. In the adult human being, this is approximately 100 ml/sec. The pressure difference from the systemic arteries to the systemic veins is about 100 mm Hg. Therefore, the resistance of the entire systemic circulation, called the *total peripheral resistance*, is about 100/100, or 1 PRU.

In conditions in which all the blood vessels throughout the body become strongly constricted, the total peripheral resistance occasionally rises to as high as 4 PRU. Conversely, when the vessels become greatly dilated, the resistance can fall to as little as 0.2 PRU.

In the pulmonary system, the mean pulmonary arterial pressure averages 16 mm Hg and the mean left atrial pressure averages 2 mm Hg, giving a net pressure difference of 14 mm. Therefore, when the cardiac output is normal at about 100 ml/sec, the *total pulmonary vascular resistance* calculates to be about 0.14 PRU (about one seventh that in the systemic circulation).

“Conductance” of Blood in a Vessel Is the Reciprocal of Resistance. Conductance is a measure of the blood flow through a vessel for a given pressure difference. This measurement is generally expressed in terms of milliliters

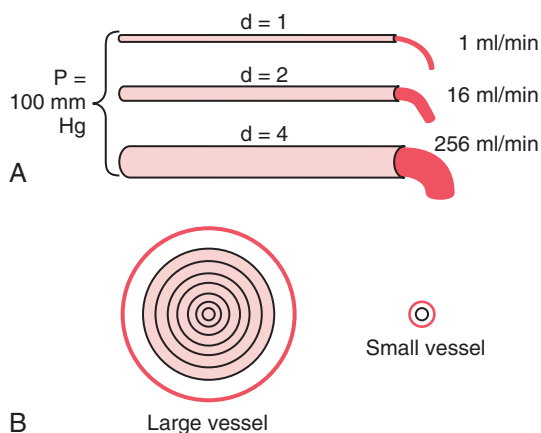


Figure 14-8. **A**, Demonstration of the effect of vessel diameter on blood flow. **B**, Concentric rings of blood flowing at different velocities; the farther away from the vessel wall, the faster the flow. *d*, diameter; *P*, pressure difference between the two ends of the vessels.

per second per millimeter of mercury pressure, but it can also be expressed in terms of liters per second per millimeter of mercury or in any other units of blood flow and pressure.

It is evident that conductance is the exact reciprocal of resistance in accord with the following equation:

$$\text{Conductance} = \frac{1}{\text{Resistance}}$$

Small Changes in Vessel Diameter Markedly Change Its Conductance. Slight changes in the diameter of a vessel cause tremendous changes in the vessel's ability to conduct blood when the blood flow is streamlined. This phenomenon is demonstrated by the experiment illustrated in [Figure 14-8A](#), which shows three vessels with relative diameters of 1, 2, and 4 but with the same pressure difference of 100 mm Hg between the two ends of the vessels. Although the diameters of these vessels increase only fourfold, the respective flows are 1, 16, and 256 ml/min, which is a 256-fold increase in flow. Thus, the conductance of the vessel increases in proportion to the *fourth power of the diameter*, in accordance with the following formula:

$$\text{Conductance} \propto \text{Diameter}^4$$

Poiseuille's Law. The cause of this great increase in conductance when the diameter increases can be explained by referring to [Figure 14-8B](#), which shows cross sections of a large and a small vessel. The concentric rings inside the vessels indicate that the velocity of flow in each ring is different from that in the adjacent rings because of *laminar* flow, which was discussed earlier in the chapter. That is, the blood in the ring touching the wall of the vessel is barely flowing because of its adherence to the vascular endothelium. The next ring of blood toward the center of the vessel slips past the first ring and, therefore,

flows more rapidly. The third, fourth, fifth, and sixth rings likewise flow at progressively increasing velocities. Thus, the blood that is near the wall of the vessel flows slowly, whereas that in the middle of the vessel flows much more rapidly.

In the small vessel, essentially all the blood is near the wall, so the extremely rapidly flowing central stream of blood simply does not exist. By integrating the velocities of all the concentric rings of flowing blood and multiplying them by the areas of the rings, one can derive the following formula, known as *Poiseuille's law*:

$$F \rightarrow \frac{\pi \Delta P r^4}{8 \eta l}$$

in which F is the rate of blood flow, ΔP is the pressure difference between the ends of the vessel, r is the radius of the vessel, l is length of the vessel, and η is viscosity of the blood.

Note particularly in this equation that the rate of blood flow is directly proportional to the *fourth power of the radius* of the vessel, which demonstrates once again that the diameter of a blood vessel (which is equal to twice the radius) plays by far the greatest role of all factors in determining the rate of blood flow through a vessel.

Importance of the Vessel Diameter "Fourth Power Law" in Determining Arteriolar Resistance. In the systemic circulation, about two thirds of the total systemic resistance to blood flow is arteriolar resistance in the small arterioles. The internal diameters of the arterioles range from as little as 4 micrometers to as great as 25 micrometers. However, their strong vascular walls allow the internal diameters to change tremendously, often as much as fourfold. From the fourth power law discussed earlier that relates blood flow to diameter of the vessel, one can see that a fourfold increase in vessel diameter can increase the flow as much as 256-fold. Thus, this fourth power law makes it possible for the arterioles, responding with only small changes in diameter to nervous signals or local tissue chemical signals, either to turn off almost completely the blood flow to the tissue or at the other extreme to cause a vast increase in flow. Indeed, ranges of blood flow of more than 100-fold in separate tissue areas have been recorded between the limits of maximum arteriolar constriction and maximum arteriolar dilation.

Resistance to Blood Flow in Series and Parallel Vascular Circuits. Blood pumped by the heart flows from the high-pressure part of the systemic circulation (i.e., aorta) to the low-pressure side (i.e., vena cava) through many miles of blood vessels arranged in series and in parallel. The arteries, arterioles, capillaries, venules, and veins are collectively arranged in series. When blood vessels are arranged in series, flow through each blood vessel is the same and the total resistance to blood flow (R_{total}) is equal to the sum of the resistances of each vessel:

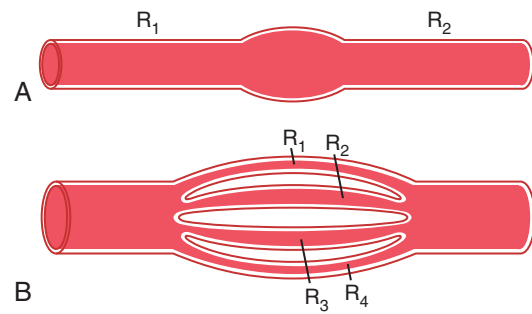


Figure 14-9. Vascular resistances (R): **A**, in series and **B**, in parallel.

$$R_{\text{total}} = R_1 + R_2 + R_3 + R_4 \dots$$

The total peripheral vascular resistance is therefore equal to the sum of resistances of the arteries, arterioles, capillaries, venules, and veins. In the example shown in **Figure 14-9A**, the total vascular resistance is equal to the sum of R_1 and R_2 .

Blood vessels branch extensively to form parallel circuits that supply blood to the many organs and tissues of the body. This parallel arrangement permits each tissue to regulate its own blood flow, to a great extent, independently of flow to other tissues.

For blood vessels arranged in parallel (**Figure 14-9B**), the total resistance to blood flow is expressed as:

$$\frac{1}{R_{\text{total}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \dots$$

It is obvious that for a given pressure gradient, far greater amounts of blood will flow through this parallel system than through any of the individual blood vessels. Therefore, the total resistance is far less than the resistance of any single blood vessel. Flow through each of the parallel vessels in **Figure 14-9B** is determined by the pressure gradient and its own resistance, not the resistance of the other parallel blood vessels. However, increasing the resistance of any of the blood vessels increases the total vascular resistance.

It may seem paradoxical that adding more blood vessels to a circuit reduces the total vascular resistance. Many parallel blood vessels, however, make it easier for blood to flow through the circuit because each parallel vessel provides another pathway, or *conductance*, for blood flow. The total conductance (C_{total}) for blood flow is the sum of the conductance of each parallel pathway:

$$C_{\text{total}} = C_1 + C_2 + C_3 + C_4 \dots$$

For example, brain, kidney, muscle, gastrointestinal, skin, and coronary circulations are arranged in parallel, and each tissue contributes to the overall conductance of the systemic circulation. Blood flow through each tissue is a fraction of the total blood flow (cardiac output) and is determined by the resistance (the reciprocal of conductance) for blood flow in the tissue, as well as the pressure gradient. Therefore, amputation of a limb or surgical

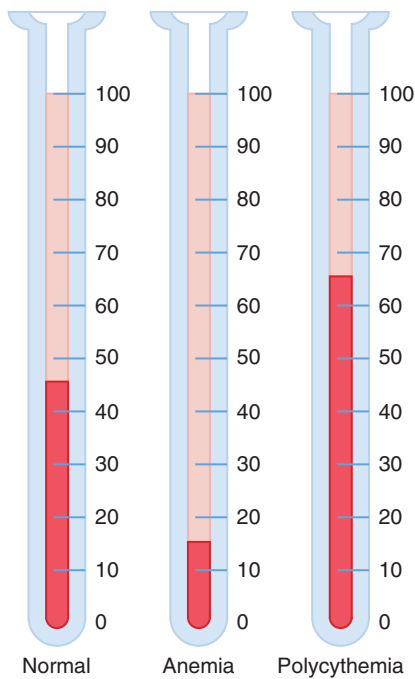


Figure 14-10. Hematocrits in a healthy (normal) person and in patients with anemia and polycythemia. The numbers refer to percentage of the blood composed of red blood cells.

removal of a kidney also removes a parallel circuit and reduces the total vascular conductance and total blood flow (i.e., cardiac output) while increasing total peripheral vascular resistance.

Effect of Blood Hematocrit and Blood Viscosity on Vascular Resistance and Blood Flow

Note that another important factor in Poiseuille's equation is the viscosity of the blood. The greater the viscosity, the lower the flow in a vessel if all other factors are constant. Furthermore, *the viscosity of normal blood is about three times as great as the viscosity of water.*

What makes the blood so viscous? It is mainly the large numbers of suspended red cells in the blood, each of which exerts frictional drag against adjacent cells and against the wall of the blood vessel.

Hematocrit—the Proportion of Blood That Is Red Blood Cells. If a person has a hematocrit of 40, this means that 40 percent of the blood volume is cells and the remainder is plasma. The hematocrit of adult men averages about 42, whereas that of women averages about 38. These values vary tremendously, depending on whether the person has anemia, the degree of bodily activity, and the altitude at which the person resides. These changes in hematocrit are discussed in relation to the red blood cells and their oxygen transport function in Chapter 33.

Hematocrit is determined by centrifuging blood in a calibrated tube, as shown in **Figure 14-10**. The calibration allows direct reading of the percentage of cells.

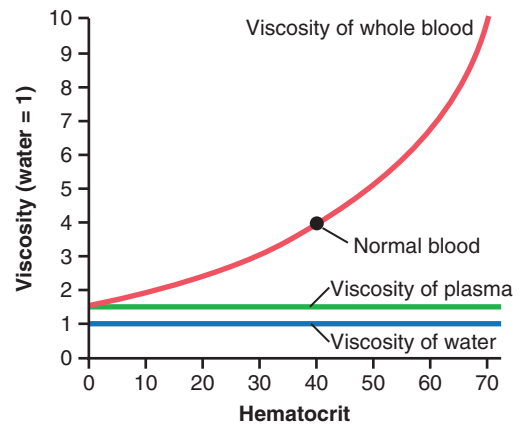


Figure 14-11. Effect of hematocrit on blood viscosity (water viscosity = 1).

Increasing Hematocrit Markedly Increases Blood Viscosity. The viscosity of blood increases drastically as the hematocrit increases, as shown in **Figure 14-11**. The viscosity of whole blood at normal hematocrit is about 3 to 4, which means that three to four times as much pressure is required to force whole blood as to force water through the same blood vessel. When the hematocrit rises to 60 or 70, which it often does in persons with *polycythemia*, the blood viscosity can become as great as 10 times that of water, and its flow through blood vessels is greatly retarded.

Other factors that affect blood viscosity are the plasma protein concentration and types of proteins in the plasma, but these effects are so much less than the effect of hematocrit that they are not significant considerations in most hemodynamic studies. The viscosity of blood plasma is about 1.5 times that of water.

EFFECTS OF PRESSURE ON VASCULAR RESISTANCE AND TISSUE BLOOD FLOW

“Autoregulation” Attenuates the Effect of Arterial Pressure on Tissue Blood Flow. From the discussion thus far, one might expect an increase in arterial pressure to cause a proportionate increase in blood flow through the various tissues of the body. However, the effect of arterial pressure on blood flow in many tissues is usually far less than one might expect, as shown in **Figure 14-12**. The reason for this is that an increase in arterial pressure not only increases the force that pushes blood through the vessels but also initiates compensatory increases in vascular resistance within a few seconds through activation of the local control mechanisms discussed in Chapter 17. Conversely, with reductions in arterial pressure, vascular resistance is promptly reduced in most tissues and blood flow is maintained at a relatively constant rate. The ability of each tissue to adjust its vascular resistance and to maintain normal blood flow during changes in arterial pressure between approximately 70 and 175 mm Hg is called *blood flow autoregulation*.

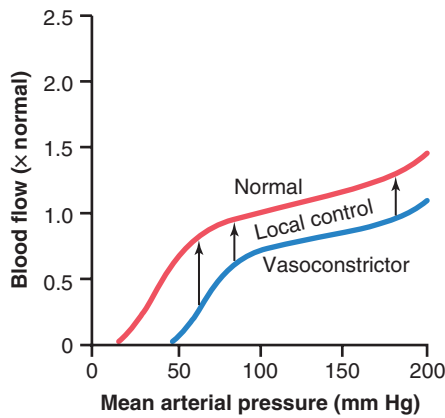


Figure 14-12. Effect of changes in arterial pressure over a period of several minutes on blood flow in a tissue such as skeletal muscle. Note that between pressure of 70 and 175 mm Hg, blood flow is “autoregulated.” The blue line shows the effect of sympathetic nerve stimulation or vasoconstriction by hormones such as norepinephrine, angiotensin II, vasopressin, or endothelin on this relationship. Reduced tissue blood flow is rarely maintained for more than a few hours because of the activation of local autoregulatory mechanisms that eventually return blood flow toward normal.

Note in **Figure 14-12** that changes in blood flow can be caused by strong sympathetic stimulation, which *constricts* the blood vessels. Likewise, hormonal vasoconstrictors, such as *norepinephrine*, *angiotensin II*, *vasopressin*, or *endothelin*, can also reduce blood flow, at least transiently.

Blood flow changes rarely last for more than a few hours in most tissues even when increases in arterial pressure or increased levels of vasoconstrictors are sustained. The reason for the relative constancy of blood flow is that each tissue’s local autoregulatory mechanisms eventually override most of the effects of vasoconstrictors to provide a blood flow that is appropriate for the needs of the tissue.

Pressure-Flow Relationship in Passive Vascular Beds.

In isolated blood vessels or in tissues that do not exhibit autoregulation, changes in arterial pressure may have important effects on blood flow. In fact, the effect of pressure on blood flow may be greater than predicted by Poiseuille’s equation, as shown by the upward curving lines in **Figure 14-13**. The reason for this is that increased arterial pressure not only increases the force that pushes

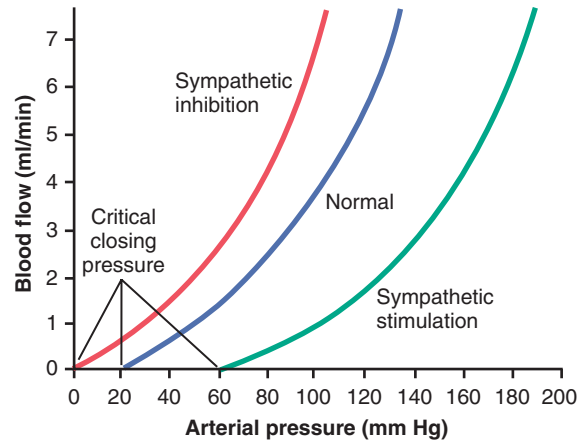


Figure 14-13. Effect of arterial pressure on blood flow through a *passive* blood vessel at different degrees of vascular tone caused by increased or decreased sympathetic stimulation of the vessel.

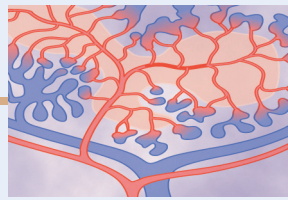
blood through the vessels but also distends the elastic vessels, actually *decreasing* vascular resistance. Conversely, decreased arterial pressure in passive blood vessels increases resistance as the elastic vessels gradually collapse due to reduced distending pressure. When pressure falls below a critical level, called the *critical closing pressure*, flow ceases as the blood vessels are completely collapsed.

Sympathetic stimulation and other vasoconstrictors can alter the passive pressure-flow relationship shown in **Figure 14-13**. Thus, *inhibition of* sympathetic activity *greatly dilates* the vessels and can increase the blood flow twofold or more. Conversely, very strong sympathetic stimulation *can constrict* the vessels so much that blood flow occasionally decreases to as low as zero for a few seconds despite high arterial pressure.

In reality, there are few physiological conditions in which tissues display the passive pressure-flow relationship shown in **Figure 14-13**. Even in tissues that do not effectively autoregulate blood flow during acute changes in arterial pressure, blood flow is regulated according to the needs of the tissue when the pressure changes are sustained, as discussed in Chapter 17.

Bibliography

See the Bibliography for Chapter 15.



Vascular Distensibility and Functions of the Arterial and Venous Systems

VASCULAR DISTENSIBILITY

A valuable characteristic of the vascular system is that all blood vessels are *distensible*. The distensible nature of the arteries allows them to accommodate the pulsatile output of the heart and to average out the pressure pulsations. This capability provides smooth, continuous flow of blood through the very small blood vessels of the tissues.

The most distensible by far of all the vessels are the veins. Even slight increases in venous pressure cause the veins to store 0.5 to 1.0 liter of extra blood. Therefore, *the veins provide a reservoir* for storing large quantities of extra blood that can be called into use whenever blood is required elsewhere in the circulation.

Units of Vascular Distensibility. Vascular distensibility normally is expressed as the fractional increase in volume for each millimeter of mercury rise in pressure, in accordance with the following formula:

$$\text{Vascular distensibility} = \frac{\text{Increase in volume}}{\text{Increase in pressure} \times \text{Original volume}}$$

That is, if 1 mm Hg causes a vessel that originally contained 10 millimeters of blood to increase its volume by 1 milliliter, the distensibility would be 0.1 per mm Hg, or 10 percent per mm Hg.

The Veins Are Much More Distensible Than the Arteries. The walls of the arteries are thicker and far stronger than those of the veins. Consequently, the veins, on average, are about eight times more distensible than the arteries. That is, a given increase in pressure causes about eight times as much increase in blood in a vein as in an artery of comparable size.

In the pulmonary circulation, the pulmonary vein distensibilities are similar to those of the systemic circulation. However, the pulmonary arteries normally operate under pressures about one sixth of those in the systemic arterial system, and their distensibilities are correspondingly greater—about six times the distensibility of systemic arteries.

VASCULAR COMPLIANCE (OR VASCULAR CAPACITANCE)

In hemodynamic studies, it usually is much more important to know the *total quantity of blood* that can be stored in a given portion of the circulation for each mm Hg pressure rise than to know the distensibilities of the individual vessels. This value is called the *compliance* or *capacitance* of the respective vascular bed; that is,

$$\text{Vascular compliance} = \frac{\text{Increase in volume}}{\text{Increase in pressure}}$$

Compliance and distensibility are quite different. A highly distensible vessel that has a small volume may have far less compliance than a much less distensible vessel that has a large volume because *compliance is equal to distensibility times volume*.

The compliance of a systemic vein is about 24 times that of its corresponding artery because it is about 8 times as distensible and has a volume about 3 times as great ($8 \times 3 = 24$).

VOLUME-PRESSURE CURVES OF THE ARTERIAL AND VENOUS CIRCULATIONS

A convenient method for expressing the relation of pressure to volume in a vessel or in any portion of the circulation is to use a *volume-pressure curve*. The red and blue solid curves in **Figure 15-1** represent, respectively, the volume-pressure curves of the normal systemic arterial system and venous system, showing that when the arterial system of the average adult person (including all the large arteries, small arteries, and arterioles) is filled with about 700 milliliters of blood, the mean arterial pressure is 100 mm Hg, but when it is filled with only 400 milliliters of blood, the pressure falls to zero.

In the entire systemic venous system, the volume normally ranges from 2000 to 3500 milliliters, and a change of several hundred milliliters in this volume is required to change the venous pressure only 3 to 5 mm Hg. This requirement mainly explains why as much as one-half liter of blood can be transfused into a healthy person in

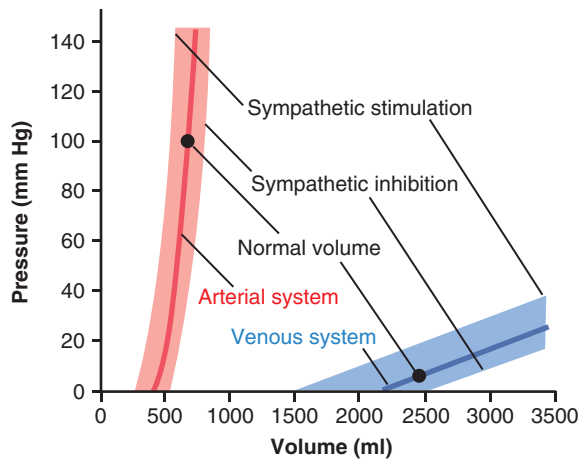


Figure 15-1. Volume-pressure curves of the systemic arterial and venous systems, showing the effects of stimulation or inhibition of the sympathetic nerves to the circulatory system.

only a few minutes without greatly altering the function of the circulation.

Effect of Sympathetic Stimulation or Sympathetic Inhibition on the Volume-Pressure Relations of the Arterial and Venous Systems. Also shown in [Figure 15-1](#) are the effects on the volume-pressure curves when the vascular sympathetic nerves are excited or inhibited. It is evident that an increase in vascular smooth muscle tone caused by sympathetic stimulation increases the pressure at each volume of the arteries or veins, whereas sympathetic inhibition decreases the pressure at each volume. Control of the vessels in this manner by the sympathetics is a valuable means for diminishing the dimensions of one segment of the circulation, thus transferring blood to other segments. For instance, an increase in vascular tone throughout the systemic circulation can cause large volumes of blood to shift into the heart, which is one of the principal methods that the body uses to rapidly increase heart pumping.

Sympathetic control of vascular capacitance is also highly important during hemorrhage. Enhancement of sympathetic tone, especially to the veins, reduces the vessel sizes enough that the circulation continues to operate almost normally even when as much as 25 percent of the total blood volume has been lost.

Delayed Compliance (Stress-Relaxation) of Vessels

The term “delayed compliance” means that a vessel exposed to increased volume at first exhibits a large increase in pressure, but progressive delayed stretching of smooth muscle in the vessel wall allows the pressure to return toward normal over a period of minutes to hours. This effect is shown in [Figure 15-2](#). In this figure, the pressure is recorded in a small segment of a vein that is occluded at both ends. An extra volume of blood is suddenly injected until the pressure rises from 5 to

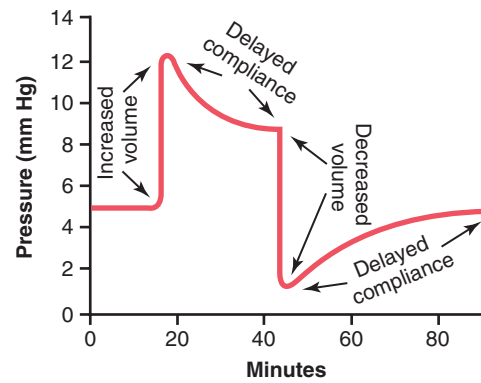


Figure 15-2. Effect on the intravascular pressure of injecting a volume of blood into a venous segment and later removing the excess blood, demonstrating the principle of delayed compliance.

12 mm Hg. Even though none of the blood is removed after it is injected, the pressure begins to decrease immediately and approaches about 9 mm Hg after several minutes. In other words, the volume of blood injected causes immediate *elastic* distention of the vein, but then the smooth muscle fibers of the vein begin to “creep” to longer lengths, and their tensions correspondingly decrease. This effect is a characteristic of all smooth muscle tissue and is called *stress-relaxation*, which was explained in Chapter 8.

Delayed compliance is a valuable mechanism by which the circulation can accommodate extra blood when necessary, such as after too large a transfusion. Delayed compliance in the reverse direction is one of the ways in which the circulation automatically adjusts itself over a period of minutes or hours to diminished blood volume after serious hemorrhage.

ARTERIAL PRESSURE PULSATATIONS

With each beat of the heart a new surge of blood fills the arteries. Were it not for distensibility of the arterial system, all of this new blood would have to flow through the peripheral blood vessels almost instantaneously, only during cardiac systole, and no flow would occur during diastole. However, the compliance of the arterial tree normally reduces the pressure pulsations to almost no pulsations by the time the blood reaches the capillaries; therefore, tissue blood flow is mainly continuous with very little pulsation.

The *pressure pulsations* at the root of the aorta are illustrated in [Figure 15-3](#). In the healthy young adult, the pressure at the top of each pulse, called the *systolic pressure*, is about 120 mm Hg. At the lowest point of each pulse, called the *diastolic pressure*, it is about 80 mm Hg. The difference between these two pressures, about 40 mm Hg, is called the *pulse pressure*.

Two major factors affect the pulse pressure: (1) the *stroke volume output* of the heart and (2) the *compliance* (*total distensibility*) of the arterial tree. A third, less

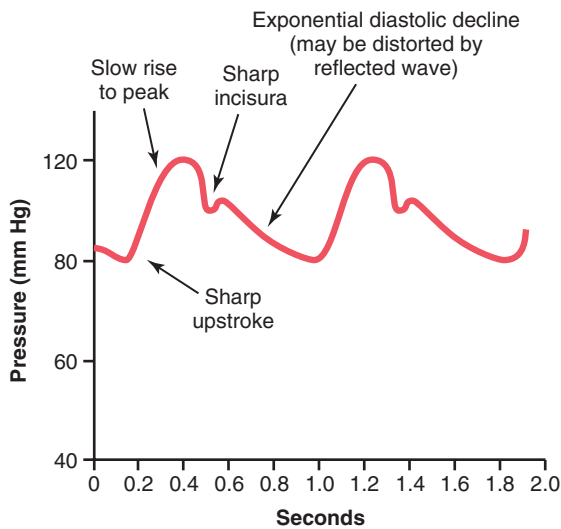


Figure 15-3. Pressure pulse contour in the ascending aorta.

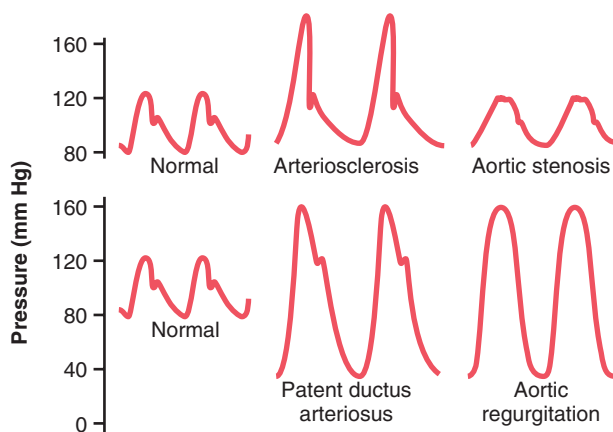


Figure 15-4. Aortic pressure pulse contours in arteriosclerosis, aortic stenosis, patent ductus arteriosus, and aortic regurgitation.

important factor is the character of ejection from the heart during systole.

In general, the greater the stroke volume output, the greater the amount of blood that must be accommodated in the arterial tree with each heartbeat, and, therefore, the greater the pressure rise and fall during systole and diastole, thus causing a greater pulse pressure. Conversely, the less the compliance of the arterial system, the greater the rise in pressure for a given stroke volume of blood pumped into the arteries. For instance, as demonstrated by the middle top curves in Figure 15-4, the pulse pressure in old age sometimes rises to twice normal because the arteries have become hardened with *arteriosclerosis* and therefore are relatively noncompliant.

In effect, pulse pressure is determined approximately by the *ratio of stroke volume output to compliance of the arterial tree*. Any condition of the circulation that affects either of these two factors also affects the pulse pressure:

$$\text{Pulse pressure} \approx \text{Stroke volume} / \text{arterial compliance}$$

ABNORMAL PRESSURE PULSE CONTOURS

Some pathophysiological conditions of the circulation cause *abnormal contours of the pressure pulse wave* in addition to altering the pulse pressure. Especially distinctive among these conditions are aortic stenosis, patent ductus arteriosus, and aortic regurgitation, each of which is shown in Figure 15-4.

In persons with *aortic valve stenosis*, the diameter of the aortic valve opening is reduced significantly, and the aortic pressure pulse is decreased significantly because of diminished blood flow outward through the stenotic valve.

In persons with *patent ductus arteriosus*, one half or more of the blood pumped into the aorta by the left ventricle flows immediately backward through the wide-open ductus into the pulmonary artery and lung blood vessels, thus allowing the diastolic pressure to fall very low before the next heartbeat.

In persons with *aortic regurgitation*, the aortic valve is absent or does not close completely. Therefore, after each heartbeat, the blood that has just been pumped into the aorta flows immediately backward into the left ventricle. As a result, the aortic pressure can fall all the way to zero between heartbeats. Also, there is no incisura in the aortic pulse contour because there is no aortic valve to close.

TRANSMISSION OF PRESSURE PULSES TO THE PERIPHERAL ARTERIES

When the heart ejects blood into the aorta during systole, at first only the proximal portion of the aorta becomes distended because the inertia of the blood prevents sudden blood movement all the way to the periphery. However, the rising pressure in the proximal aorta rapidly overcomes this inertia, and the wave front of distention spreads farther and farther along the aorta, as shown in Figure 15-5. This phenomenon is called *transmission of the pressure pulse* in the arteries.

The velocity of pressure pulse transmission is 3 to 5 m/sec in the normal aorta, 7 to 10 m/sec in the large arterial branches, and 15 to 35 m/sec in the small arteries. In general, the greater the compliance of each vascular segment, the slower the velocity, which explains the slow transmission in the aorta and the much faster transmission in the much less compliant small distal arteries. In the aorta, the velocity of transmission of the pressure pulse is 15 or more times the velocity of blood flow because the pressure pulse is simply a moving wave of *pressure* that involves little forward total movement of blood volume.

Pressure Pulses Are Damped in the Smaller Arteries, Arterioles, and Capillaries. Figure 15-6 shows typical changes in the contours of the pressure pulse as the pulse travels into the peripheral vessels. Note especially in the three lower curves that the intensity of pulsation becomes

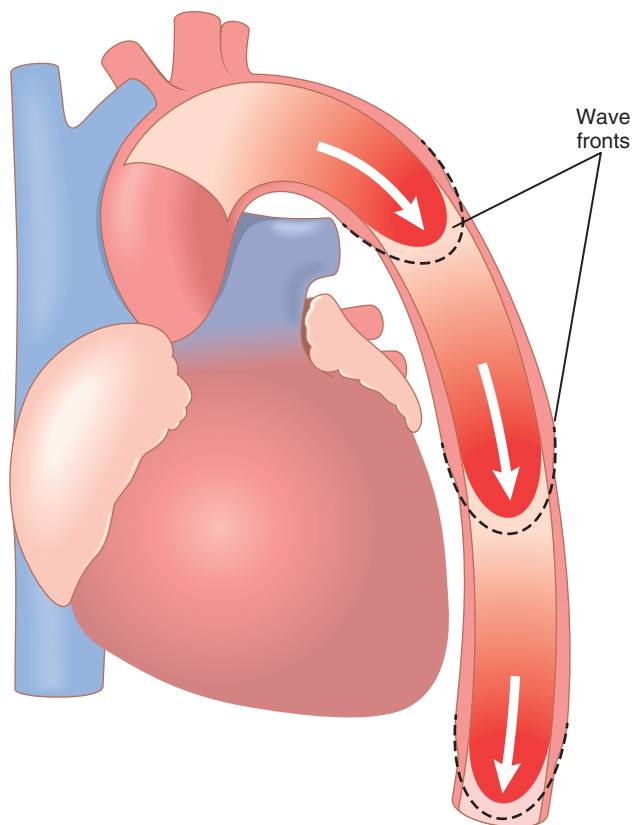


Figure 15-5. Progressive stages in transmission of the pressure pulse along the aorta.

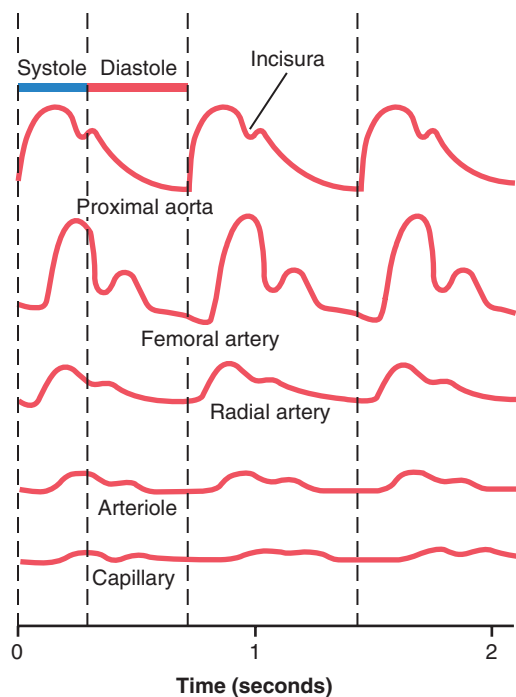


Figure 15-6. Changes in the pulse pressure contour as the pulse wave travels toward the smaller vessels.

progressively less in the smaller arteries, the arterioles, and, especially, the capillaries. In fact, only when the aortic pulsations are extremely large or the arterioles are greatly dilated can pulsations be observed in the capillaries.

This progressive diminution of the pulsations in the periphery is called *damping* of the pressure pulses. The cause of this damping is twofold: (1) resistance to blood movement in the vessels, and (2) compliance of the vessels. The resistance damps the pulsations because a small amount of blood must flow forward at the pulse wave front to distend the next segment of the vessel; the greater the resistance, the more difficult it is for this to occur. The compliance damps the pulsations because the more compliant a vessel, the greater the quantity of blood required at the pulse wave front to cause an increase in pressure. Therefore, *the degree of damping is almost directly proportional to the product of resistance times compliance.*

CLINICAL METHODS FOR MEASURING SYSTOLIC AND DIASTOLIC PRESSURES

It is not practical to use pressure recorders that require needle insertion into an artery for making routine arterial pressure measurements in human patients, although these types of recorders are used on occasion when special studies are necessary. Instead, the clinician determines systolic and diastolic pressures through indirect means, usually by the *auscultatory method*.

Auscultatory Method. **Figure 15-7** shows the auscultatory method for determining systolic and diastolic arterial pressures. A stethoscope is placed over the antecubital artery and a blood pressure cuff is inflated around the upper arm. As long as the cuff continues to compress the arm with too little pressure to close the brachial artery with the stethoscope. However, when the cuff pressure is great enough to close the artery during part of the arterial pressure cycle, a sound is then heard with each pulsation. These sounds are called *Korotkoff sounds*, named after Nikolai Korotkoff, a Russian physician who described them in 1905.

The Korotkoff sounds are believed to be caused mainly by blood jetting through the partly occluded vessel and by vibrations of the vessel wall. The jet causes turbulence in the vessel beyond the cuff, and this turbulence sets up the vibrations heard through the stethoscope.

In determining blood pressure by the auscultatory method, the pressure in the cuff is first elevated well above arterial systolic pressure. As long as this cuff pressure is higher than systolic pressure, the brachial artery remains collapsed so that no blood jets into the lower artery during any part of the pressure cycle. Therefore, no Korotkoff sounds are heard in the lower artery. But then the cuff pressure gradually is reduced. Just as soon as the pressure in the cuff falls below systolic pressure (**point B**,

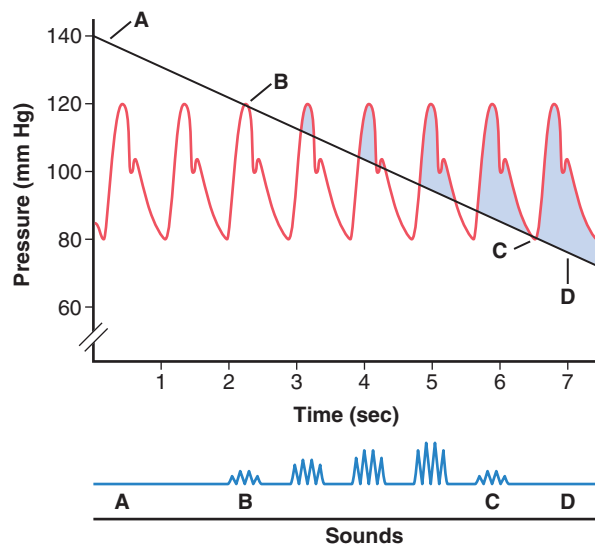


Figure 15-7. The auscultatory method for measuring systolic and diastolic arterial pressures.

Figure 15-7), blood begins to flow through the artery beneath the cuff during the peak of systolic pressure, and one begins to hear *tapping* sounds from the antecubital artery in synchrony with the heartbeat. As soon as these sounds begin to be heard, the pressure level indicated by the manometer connected to the cuff is about equal to the systolic pressure.

As the pressure in the cuff is lowered still more, the Korotkoff sounds change in quality, having less of the tapping quality and more of a rhythmical and harsher quality. Then, finally, when the pressure in the cuff falls near diastolic pressure, the sounds suddenly change to a muffled quality (**point C**, **Figure 15-7**). One notes the manometer pressure when the Korotkoff sounds change to the muffled quality, and this pressure is about equal to the diastolic pressure, although it slightly overestimates

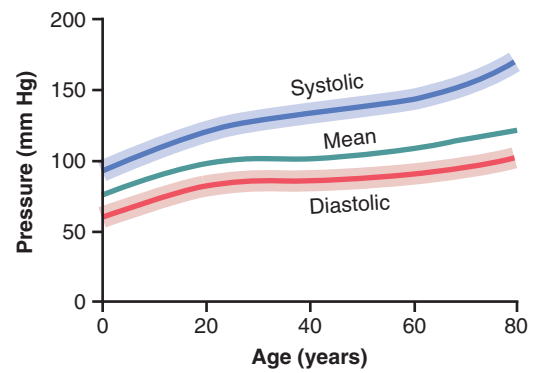


Figure 15-8. Changes in systolic, diastolic, and mean arterial pressures with age. The shaded areas show the approximate normal ranges.

the diastolic pressure determined by direct intra-arterial catheter. As the cuff pressure falls a few mm Hg further, the artery no longer closes during diastole, which means that the basic factor causing the sounds (the jetting of blood through a squeezed artery) is no longer present. Therefore, the sounds disappear entirely. Many clinicians believe that the pressure at which the Korotkoff sounds completely disappear should be used as the diastolic pressure, except in situations in which the disappearance of sounds cannot reliably be determined because sounds are audible even after complete deflation of the cuff. For example, in patients with arteriovenous fistulas for hemodialysis or with aortic insufficiency, Korotkoff sounds may be heard after complete deflation of the cuff.

The auscultatory method for determining systolic and diastolic pressures is not entirely accurate, but it usually gives values within 10 percent of those determined by direct catheter measurement from inside the arteries.

Normal Arterial Pressures as Measured by the Auscultatory Method. **Figure 15-8** shows the approximate normal systolic and diastolic arterial pressures at different ages. The progressive increase in pressure with age results from the effects of aging on the blood pressure control mechanisms. We shall see in Chapter 19 that the kidneys are primarily responsible for this long-term regulation of arterial pressure; it is well known that the kidneys exhibit definitive changes with age, especially after the age of 50 years.

A slight extra increase in *systolic* pressure usually occurs beyond the age of 60 years. This increase results from decreasing distensibility, or “hardening,” of the arteries, which is often a result of *atherosclerosis*. The final effect is a higher systolic pressure with considerable increase in pulse pressure, as previously explained.

Mean Arterial Pressure. The mean arterial pressure is the average of the arterial pressures measured millisecond by millisecond over a period of time. It is not equal to the average of systolic and diastolic pressure because at normal heart rates, a greater fraction of the cardiac cycle

is spent in diastole than is systole; thus, the arterial pressure remains nearer to diastolic pressure than to systolic pressure during the greater part of the cardiac cycle. The mean arterial pressure is therefore determined about 60 percent by the diastolic pressure and 40 percent by the systolic pressure. Note in **Figure 15-8** that the mean pressure (*solid green line*) at all ages is nearer to the diastolic pressure than to the systolic pressure. However, at very high heart rates, diastole comprises a smaller fraction of the cardiac cycle and the mean arterial pressure is more closely approximated as the average of systolic and diastolic pressures.

VEINS AND THEIR FUNCTIONS

The veins provide passageways for flow of blood to the heart, but they also perform other special functions that are necessary for operation of the circulation. Of special importance is that they are capable of constricting and enlarging and thereby storing either small or large quantities of blood and making this blood available when it is required by the remainder of the circulation. The peripheral veins can also propel blood forward by means of a so-called *venous pump*, and they even help to regulate cardiac output, an exceedingly important function that is described in detail in Chapter 20.

VENOUS PRESSURES—RIGHT ATRIAL PRESSURE (CENTRAL VENOUS PRESSURE) AND PERIPHERAL VENOUS PRESSURES

To understand the various functions of the veins, it is first necessary to know something about pressure in the veins and what determines the pressure.

Blood from all the systemic veins flows into the right atrium of the heart; therefore, the pressure in the right atrium is called the *central venous pressure*.

Right atrial pressure is regulated by a balance between (1) the ability of the heart to pump blood out of the right atrium and ventricle into the lungs and (2) the tendency for blood to flow from the peripheral veins into the right atrium. If the right heart is pumping strongly, the right atrial pressure decreases. Conversely, weakness of the heart elevates the right atrial pressure. Also, any effect that causes rapid inflow of blood into the right atrium from the peripheral veins elevates the right atrial pressure. Some of the factors that can increase this venous return and thereby increase the right atrial pressure are (1) increased blood volume, (2) increased large vessel tone throughout the body with resultant increased peripheral venous pressures, and (3) dilation of the arterioles, which decreases the peripheral resistance and allows rapid flow of blood from the arteries into the veins.

The same factors that regulate right atrial pressure also contribute to regulation of cardiac output because the amount of blood pumped by the heart depends on both the ability of the heart to pump and the tendency for

blood to flow into the heart from the peripheral vessels. Therefore, we discuss regulation of right atrial pressure in much more depth in Chapter 20 in connection with regulation of cardiac output.

The *normal right atrial pressure* is about 0 mm Hg, which is equal to the atmospheric pressure around the body. It can increase to 20 to 30 mm Hg under very abnormal conditions, such as (1) serious heart failure or (2) after massive transfusion of blood, which greatly increases the total blood volume and causes excessive quantities of blood to attempt to flow into the heart from the peripheral vessels.

The lower limit to the right atrial pressure is usually about -3 to -5 mm Hg below atmospheric pressure, which is also the pressure in the chest cavity that surrounds the heart. The right atrial pressure approaches these low values when the heart pumps with exceptional vigor or when blood flow into the heart from the peripheral vessels is greatly depressed, such as after severe hemorrhage.

Venous Resistance and Peripheral Venous Pressure

Large veins have so little resistance to blood flow *when they are distended* that the resistance then is almost zero and is of almost no importance. However, as shown in **Figure 15-9**, most of the large veins that enter the thorax are compressed at many points by the surrounding tissues so that blood flow is impeded at these points. For instance, the veins from the arms are compressed by their sharp angulations over the first rib. Also, the pressure in the neck veins often falls so low that the atmospheric pressure on the outside of the neck causes these veins to collapse. Finally, veins coursing through the abdomen are often compressed by different organs and by the intra-abdominal

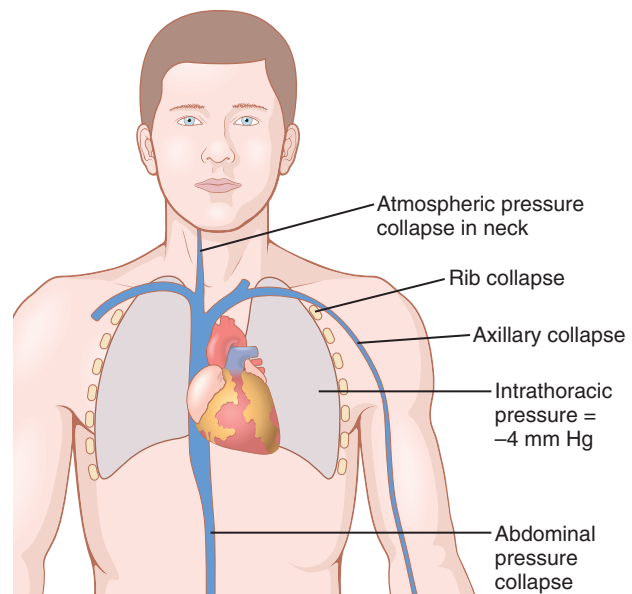


Figure 15-9. Compression points that tend to collapse the veins entering the thorax.

pressure, so they usually are at least partially collapsed to an ovoid or slit-like state. For these reasons, the *large veins do usually offer some resistance to blood flow*, and thus the pressure in the more peripheral small veins in a person lying down is usually +4 to +6 mm Hg greater than the right atrial pressure.

Effect of High Right Atrial Pressure on Peripheral Venous Pressure. When the right atrial pressure rises above its normal value of 0 mm Hg, blood begins to back up in the large veins. This backup of blood enlarges the veins, and even the collapse points in the veins open up when the right atrial pressure rises above +4 to +6 mm Hg. Then, as the right atrial pressure rises still further, the additional increase causes a corresponding rise in peripheral venous pressure in the limbs and elsewhere. Because the heart must be weakened significantly to cause a rise in right atrial pressure as high as +4 to +6 mm Hg, the peripheral venous pressure is not noticeably elevated even in the early stages of heart failure as long as the person is at rest.

Effect of Intra-abdominal Pressure on Venous Pressures of the Leg. The pressure in the abdominal cavity of a recumbent person normally averages about +6 mm Hg, but it can rise to +15 to +30 mm Hg as a result of pregnancy, large tumors, abdominal obesity, or excessive fluid (called “ascites”) in the abdominal cavity. When the intra-abdominal pressure rises, the pressure in the veins of the legs must rise *above* the abdominal pressure before the abdominal veins will open and allow the blood to flow from the legs to the heart. Thus, if the intra-abdominal pressure is +20 mm Hg, the lowest possible pressure in the femoral veins is also about +20 mm Hg.

Effect of Gravitational Pressure on Venous Pressure

In any body of water that is exposed to air, the pressure at the surface of the water is equal to atmospheric pressure, but the pressure rises 1 mm Hg for each 13.6 millimeters of distance below the surface. This pressure results from the weight of the water and therefore is called *gravitational pressure* or *hydrostatic pressure*.

Gravitational pressure also occurs in the vascular system of the human being because of weight of the blood in the vessels, as shown in **Figure 15-10**. When a person is standing, the pressure in the right atrium remains about 0 mm Hg because the heart pumps into the arteries any excess blood that attempts to accumulate at this point. However, in an adult *who is standing absolutely still*, the pressure in the veins of the feet is about +90 mm Hg simply because of the gravitational weight of the blood in the veins between the heart and the feet. The venous pressures at other levels of the body are proportionately between 0 and 90 mm Hg.

In the arm veins, the pressure at the level of the top rib is usually about +6 mm Hg because of compression

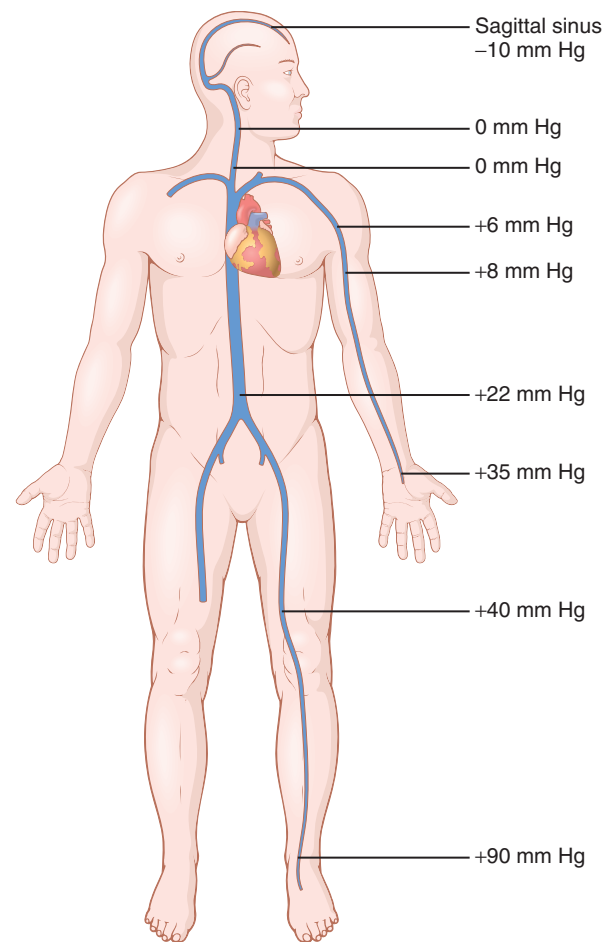


Figure 15-10. Effect of gravitational pressure on the venous pressures throughout the body in the standing person.

of the subclavian vein as it passes over this rib. The gravitational pressure down the length of the arm then is determined by the distance below the level of this rib. Thus, if the gravitational difference between the level of the rib and the hand is +29 mm Hg, this gravitational pressure is added to the +6 mm Hg pressure caused by compression of the vein as it crosses the rib, making a total of +35 mm Hg pressure in the veins of the hand.

The neck veins of a person standing upright collapse almost completely all the way to the skull because of atmospheric pressure on the outside of the neck. This collapse causes the pressure in these veins to remain at zero along their entire extent. Any tendency for the pressure to rise above this level opens the veins and allows the pressure to fall back to zero because of flow of the blood. Conversely, any tendency for the neck vein pressure to fall below zero collapses the veins still more, which further increases their resistance and again returns the pressure back to zero.

The veins inside the skull, on the other hand, are in a noncollapsible chamber (the skull cavity) and thus they cannot collapse. Consequently, *negative pressure can exist in the dural sinuses of the head*; in the standing position, the venous pressure in the sagittal sinus at the top of the

brain is about -10 mm Hg because of the hydrostatic “suction” between the top of the skull and the base of the skull. Therefore, if the sagittal sinus is opened during surgery, air can be sucked immediately into the venous system; the air may even pass downward to cause air embolism in the heart and death.

Effect of the Gravitational Factor on Arterial and Other Pressures. The gravitational factor also affects pressures in the peripheral arteries and capillaries. For instance, a standing person who has a mean arterial pressure of 100 mm Hg at the level of the heart has an arterial pressure in the feet of about 190 mm Hg. Therefore, when one states that the arterial pressure is 100 mm Hg, this statement generally means that 100 mm Hg is the pressure at the gravitational level of the heart but not necessarily elsewhere in the arterial vessels.

Venous Valves and the “Venous Pump”: Their Effects on Venous Pressure

Were it not for valves in the veins, the gravitational pressure effect would cause the venous pressure in the feet always to be about $+90$ mm Hg in a standing adult. However, every time one moves the legs, one tightens the muscles and compresses the veins in or adjacent to the muscles, which squeezes the blood out of the veins. However, the valves in the veins, shown in **Figure 15-11**, are arranged so that the direction of venous blood flow can be only toward the heart. Consequently, every time a person moves the legs or even tenses the leg muscles, a certain amount of venous blood is propelled toward the heart. This pumping system is known as the “venous pump” or “muscle pump,” and it is efficient enough that under ordinary circumstances the venous pressure in the feet of a walking adult remains less than $+20$ mm Hg.

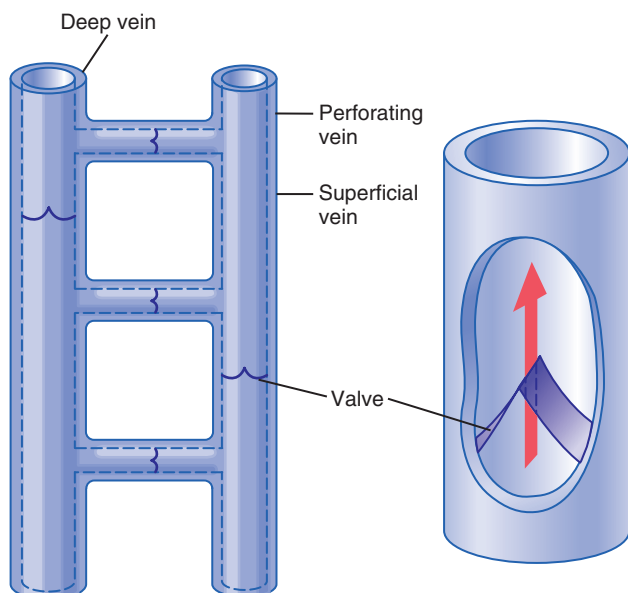


Figure 15-11. Venous valves of the leg.

If a person stands perfectly still, the venous pump does not work, and the venous pressures in the lower legs increase to the full gravitational value of 90 mm Hg in about 30 seconds. The pressures in the capillaries also increase greatly, causing fluid to leak from the circulatory system into the tissue spaces. As a result, the legs swell and the blood volume diminishes. Indeed, 10 to 20 percent of the blood volume can be lost from the circulatory system within the 15 to 30 minutes of standing absolutely still, which may lead to fainting as sometimes occurs when a soldier is made to stand at rigid attention. This situation can be avoided by simply flexing the leg muscles periodically and slightly bending the knees, thus permitting the venous pump to work.

Venous Valve Incompetence Causes “Varicose” Veins. The valves of the venous system may become “incompetent” or even be destroyed when the veins have been overstretched by excess venous pressure lasting weeks or months, which can occur in pregnancy or when one stands most of the time. Stretching the veins increases their cross-sectional areas, but the leaflets of the valves do not increase in size. Therefore, the leaflets of the valves no longer close completely. When this lack of complete closure occurs, the pressure in the veins of the legs increases greatly because of failure of the venous pump, which further increases the sizes of the veins and finally destroys the function of the valves entirely. Thus, the person develops “varicose veins,” which are characterized by large, bulbous protrusions of the veins beneath the skin of the entire leg, particularly the lower leg.

Whenever people with varicose veins stand for more than a few minutes, the venous and capillary pressures become very high and leakage of fluid from the capillaries causes constant edema in the legs. The edema in turn prevents adequate diffusion of nutritional materials from the capillaries to the muscle and skin cells, so the muscles become painful and weak and the skin may even become gangrenous and ulcerate. The best treatment for such a condition is continual elevation of the legs to a level at least as high as the heart. Tight binders or long “compression” stockings on the legs also can be of considerable assistance in preventing the edema and its sequelae.

Clinical Estimation of Venous Pressure. Venous pressure often can be estimated by simply observing the degree of distention of the peripheral veins—especially of the neck veins. For instance, in the sitting position, the neck veins are never distended in the normal quietly resting person. However, when the right atrial pressure becomes increased to as much as $+10$ mm Hg, the lower veins of the neck begin to protrude, and at $+15$ mm Hg atrial pressure, essentially all the veins in the neck become distended.

Direct Measurement of Venous Pressure and Right Atrial Pressure. Venous pressure can also be measured

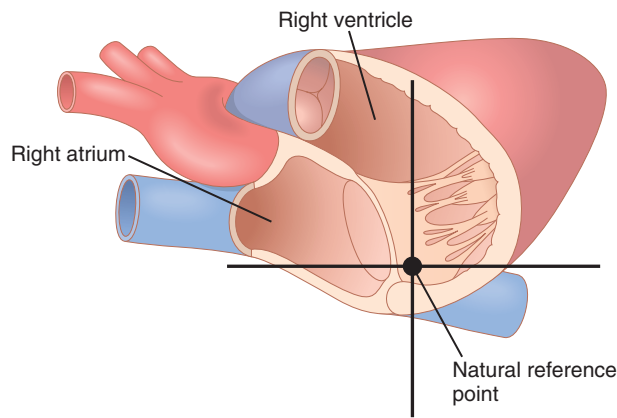


Figure 15-12. Reference point for circulatory pressure measurement (located near the tricuspid valve).

with ease by inserting a needle directly into a vein and connecting it to a pressure recorder. The only means by which *right atrial pressure* can be measured accurately is by inserting a catheter through the peripheral veins and into the right atrium. Pressures measured through such *central venous catheters* are often used in some types of hospitalized cardiac patients to provide constant assessment of heart-pumping ability.

Pressure Reference Level for Measuring Venous and Other Circulatory Pressures. In discussions up to this point, we often have spoken of right atrial pressure as being 0 mm Hg and arterial pressure as being 100 mm Hg, but we have not stated the gravitational level in the circulatory system to which this pressure is referred. There is one point in the circulatory system at which gravitational pressure factors caused by changes in body position of a healthy person usually do not affect the pressure measurement by more than 1 to 2 mm Hg. This is at or near the level of the tricuspid valve, as shown by the crossed axes in **Figure 15-12**. Therefore, all circulatory pressure measurements discussed in this text are referred to this level, which is called the *reference level for pressure measurement*.

The reason for lack of gravitational effects at the tricuspid valve is that the heart automatically prevents significant gravitational changes in pressure at this point in the following way:

If the pressure at the tricuspid valve rises slightly above normal, the right ventricle fills to a greater extent than usual, causing the heart to pump blood more rapidly and therefore to decrease the pressure at the tricuspid valve back toward the normal mean value. Conversely, if the pressure falls, the right ventricle fails to fill adequately, its pumping decreases, and blood dams up in the venous system until the pressure at the tricuspid level again rises to the normal value. In other words, *the heart acts as a feedback regulator of pressure* at the tricuspid valve.

When a person is lying on his or her back, the tricuspid valve is located at almost exactly 60 percent of the chest thickness in front of the back. This is the *zero pressure reference level* for a person lying down.

BLOOD RESERVOIR FUNCTION OF THE VEINS

As pointed out in Chapter 14, more than 60 percent of all the blood in the circulatory system is usually in the veins. For this reason, and also because the veins are so compliant, it is said that the venous system serves as a *blood reservoir* for the circulation.

When blood is lost from the body and the arterial pressure begins to fall, nervous signals are elicited from the carotid sinuses and other pressure-sensitive areas of the circulation, as discussed in Chapter 18. These signals, in turn, elicit nerve signals from the brain and spinal cord, mainly through sympathetic nerves to the veins, causing them to constrict. This process takes up much of the slack in the circulatory system caused by the lost blood. Indeed, even after as much as 20 percent of the total blood volume has been lost, the circulatory system often functions almost normally because of this variable reservoir function of the veins.

SPECIFIC BLOOD RESERVOIRS

Certain portions of the circulatory system are so extensive and/or so compliant that they are called “specific blood reservoirs.” These reservoirs include (1) the *spleen*, which sometimes can decrease in size sufficiently to release as much as 100 milliliters of blood into other areas of the circulation; (2) the *liver*, the sinuses of which can release several hundred milliliters of blood into the remainder of the circulation; (3) the *large abdominal veins*, which can contribute as much as 300 milliliters; and (4) the *venous plexus beneath the skin*, which also can contribute several hundred milliliters. The *heart* and the *lungs*, although not parts of the systemic venous reservoir system, may also be considered blood reservoirs. The heart, for instance, shrinks during sympathetic stimulation and in this way can contribute some 50 to 100 milliliters of blood; the lungs can contribute another 100 to 200 milliliters when the pulmonary pressures decrease to low values.

THE SPLEEN AS A RESERVOIR FOR STORING RED BLOOD CELLS

Figure 15-13 shows that the spleen has two separate areas for storing blood: the *venous sinuses* and the *pulp*. The sinuses can swell the same as any other part of the venous system and store whole blood.

In the splenic pulp, the capillaries are so permeable that whole blood, including the red blood cells, oozes through the capillary walls into a trabecular mesh, forming the *red pulp*. The red cells are trapped by the trabeculae, while the plasma flows on into the venous sinuses and then into the general circulation. As a consequence, the red pulp of the spleen is a *special reservoir that contains large quantities of concentrated red blood cells*. These

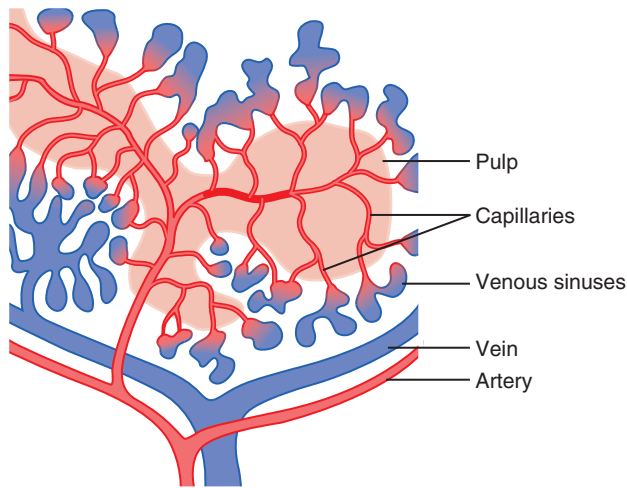


Figure 15-13. Functional structures of the spleen.

concentrated red blood cells can then be expelled into the general circulation whenever the sympathetic nervous system becomes excited and causes the spleen and its vessels to contract. As much as 50 milliliters of concentrated red blood cells can be released into the circulation, raising the hematocrit 1 to 2 percent.

In other areas of the splenic pulp are islands of white blood cells, which collectively are called the *white pulp*. Here lymphoid cells are manufactured that are similar to those manufactured in the lymph nodes. They are part of the body's immune system, described in Chapter 35.

Blood-Cleansing Function of the Spleen—Removal of Old Cells

Blood cells passing through the splenic pulp before entering the sinuses undergo thorough squeezing. Therefore, it is to be expected that fragile red blood cells would not withstand the trauma. For this reason, many of the red blood cells destroyed in the body have their final demise in the spleen. After the cells rupture, the released hemoglobin and the cell stroma are digested by the reticuloendothelial cells of the spleen, and the products of digestion are mainly reused by the body as nutrients, often for making new blood cells.

Reticuloendothelial Cells of the Spleen

The pulp of the spleen contains many large phagocytic reticuloendothelial cells, and the venous sinuses are lined with similar cells. These cells function as part of a cleansing system for the blood, acting in concert with a similar system of reticuloendothelial cells in the venous sinuses of the liver. When the blood is invaded by infectious agents, the reticuloendothelial cells of the spleen rapidly remove debris, bacteria, parasites, and so forth. Also, in many chronic infectious processes, the spleen enlarges in the same manner that lymph nodes enlarge and then performs its cleansing function even more avidly.

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